VHTR – ONGOING INTERNATIONAL PROJECTS

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I. INTRODUCTION

The world today is facing tremendous energy challenges as a result of both a demographic explosion worldwide and a fast economic development of China and India that represent 30% of the world's population. Most conservative scenarios will drive the energy demand to high levels when at the same time fossil resources are becoming scarcer and should be replaced by low carbon energy sources to limit CO_2 emissions and associated risks of climate change. Meeting the fast growing energy demand while decreasing greenhouse gas emissions calls for making an extensive use of renewable and nuclear energies to displace fossil fuels for producing electricity and other energy products such as fuels for air- and ground-transportation, as well as process heat for the industry (petro-chemistry, steel making and others…). Indeed, electricity is responsible for ~30% only of CO_2 emissions worldwide. Light water reactors can generate nuclear electricity and hydrogen through alkaline electrolysis. However, the unique capability of *Very High Temperature Reactors (VHTRs)* to produce process heat above 600°C makes them a strategic reactor type that can more efficiently produce hydrogen through steam electrolysis, or supply both hydrogen and high temperature heat for producing synthetic fuels from coal or biomass, or also supply high temperature heat and hydrogen or syngas as chemical reactant to varied industrial plants including petro-chemistry and steelmaking. Based on the past experience acquired from the 1960s through the 1980s on experimental high temperature reactors (HTRs) and prototypes, new incentives for non electricity nuclear productions add up to the attractive safety features of medium size HTRs (< 600 MW_{th}) to make VHTR the system that fosters today the most active R&D cooperation in the frame of the Generation IV International Forum (GIF) and the greatest number of national projects of prototypes in the next two decades.

II. PAST EXPERIENCE ON HTR

In the 1960s two different types of reactors were designed and built, primarily to produce electricity. Experimental HTRs with a prismatic block-core were developed in United Kingdom *(DRAGON reactor, 20 MW_{th})* and the United States *(Peach Bottom, 40 MW_e)*. They were followed by the prototype of *Fort St. Vrain Generating Station (330 MW_e)* that operated from 1979 to 1989. This reactor established the technical feasibility of HTRs even though it was beset by problems of power fluctuations, jamming of control rod and leakage of water into the core which finally caused its decommissioning for economic reasons.

Over the same period, Germany developed pebble bed reactors and built an experimental reactor *(AVR, 15 MW_e)* on the Research Centre of Jülich that successfully operated from 1966 to 1987 and gave valuable feedback on pebble fuel and overall operation. Following this experience, a 300 MW_e prototype of power reactor that was aimed at using thorium fuel was built and operated: *the Thorium High Temperature Reactor (THTR-300, 300 MW_e)*. This prototype however suffered a number of technical difficulties and was finally closed in 0icity production. No further developments were to occur until the late 1990s when the interest in HTRs was revived by needs of low carbon high temperature heat supply for varied industrial processes.

III. TODAY'S CONTEXT

First, the Japan Atomic Energy Agency (JAEA) built a research reactor in Oarai, the High Temperature engineering Test Reactor (HTTR) that was put in service in 1998 and reached its full design power of 30 MW_{th} in 1999 with an outlet helium temperature of 850°C. Subsequent tests have demonstrated the safe behavior of the reactor in various accidental sequences and the successful operation at the design temperature of 950°C. The HTTR is to restart in 2009 after 18 months at shutdown, and to proceed with a continuous operation at 950°C for 60 days. In parallel with tests on the HTTR, JAEA is developing the sulfur-iodine thermo-chemical process to produce hydrogen. A first demonstration of this process was achieved in 2003 when a continuous production of 30 litres of hydrogen per hour was obtained for a few days. The next steps are tests of a pilot plant of 400 kW (30 m^3/hr) around 2012 and tests of nuclear production coupled to the HTTR at pre-industrial scale (10 MW and 1 000 m^3/hr) around 2015-2020.

Then, Institute of Nuclear and New Energy Technology (INET) of Tsinghua University in China built the experimental reactor HTR-10 (10 MW_{th}) that was put in operation in 2000. The successful operation of this reactor demonstrated the updated pebble bed core HTR technology and paved the way for scaling up this technology into the HTR-PM project in China.

Currently, the revival of interest in high temperature process heat applications fostered R&D and projects of new builds of HTRs in the world thus preparing the advent of a new generation of this reactor type: the Very High Temperature Reactor (VHTR).

IV. ON GOING INTERNATIONAL PROJECTS

There are today in the world several projects of VHTR prototypes planned for the period 2015-2025. They are at different stages of maturity and aim at varied applications: electricity first and process heat in a second stage, or dedication to hydrogen production. The interest and support of end user industries is sought to create private / public partnerships to build and operate such prototypes and proceed with demonstrations relevant to their industrial needs. Industrial sectors concerned include the oil industry (extraction & treatment of oil sands, production of synthetic fuels from coal & biomass), as well as chemical and steel industries.

IV-A – HTR-PM in China

In 2005, China announced its intention to scale up the HTR-10 technology and to realise a national project of 200 MW_e MHTGR commercial plant with independent intellectual property rights. This project consists in two High Temperature Reactor-Pebble Bed Modules (HTR-PM)[1] of 250 MW_{th} with a helium core outlet temperature of 750°C that drive together a steam turbine of 200 MW_e. It is supported by a 3-party joint venture: the industry, the university and research organizations. The main design features of the nuclear island that were selected in 2006 are largely derived from those of the HTR-10. The basic design is completed and the preliminary safety analysis report is under review.

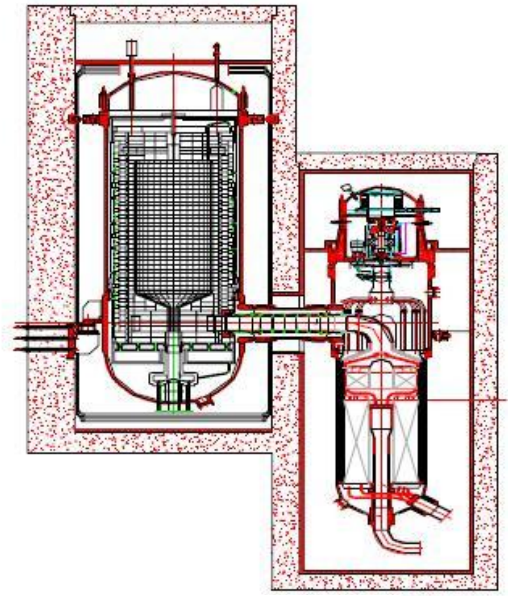

Figure 1: Primary system of HTR-PM

The construction has begun in 2009 on the site of the Shidaowan plant in the Province of Shandong with a commissioning planned in 2013. As first demonstration power plant, the HTR-PM, is not expected to be an economically self-financing project and hence the government partly funds its construction and operation so as to support the operation of the plant and guarantee the owner a fair recovery of its investment. The economic competitiveness of HTR-PM power plants is sought through modularization, batch construction and use of mature technologies to the extent possible to reduce technical risks. In this respect, best use will be made of the successful experience gained from the HTR-10 and other HTR projects abroad.

The lay-out of the nuclear island and overall design features of the HTR-PM are similar to those of the HTR-10, which have been tested for several years of operation. The conventional island will use the mature technology of high temperature and high pressure over-heat steam turbine-generator which is widely used in thermal power plants. The manufacture of fuel elements will also be based on the technology verified on the HTR-10 project. The key systems and equipments will be tested on engineering scale experimental rigs in order to guarantee the safety and reliability of the HTR-PM project. In addition, the use of mature technologies and successful experiences developed abroad is also considered through international cooperation.

After the HTR-PM demonstration plant has demonstrated a successful operation, larger scale HTR-PM power plants using multiple-modules and one steam turbine-generator will be built so as to take full benefit from standardization and modularization permitted by the technology.

A comprehensive plan supported by the government has been defined to develop and test key technologies and specific engineering features for the HTR-PM. A HTR-PM engineering laboratory and a large helium engineering testing loop, as well other large scale testing rigs are under construction at INET to test the main components of the reactor. At the same time, a fuel production line with a capacity of 300 000 fuel pebbles per year will be built in Inner Mongolia to serve HTR-PM projects.

Even though aimed operating conditions in a first stage correspond to a core outlet temperature of 750°C, the reactor is designed to achieve a core outlet temperature of 950°C with current core design and fuel element technologies. Improvements of fuel performances should enable to reach ultimately a core exit temperature of 1 000°C. Besides, the modular nature of the HTR-PM makes it possible to replace the steam turbine of the power conversion system by a helium turbine or a super critical steam turbine, as well as by a hydrogen production plant in a second stage.

IV-B – Pebble Bed Modular Reactor (PBMR) in the Republic of South Africa

Pebble Bed Modular Reactor Pty. Ltd (PBMR)[2] is a public-private partnership that was established in 1999 in the Republic of South Africa to initiate the development of a modular pebble-bed reactor with a rated capacity of 165 MW_e. This design featured a thermal power of 400 MW_{th} and a direct power conversion with a gas turbine operating with an inlet helium temperature of 750-900°C. In June 2003 the government of the Republic of South Africa approved a prototype of pebble-bed modular reactor of 110 MW_e for Eskom on the site of Koeberg. This prototype that was intended to be put in service in 2014 was meant to precede a series of 24 PBMRs so as to make up 4 000 MW_e out of the 12 000 MW_e additional nuclear capacity planned by 2030. Facilities dedicated to PBMR specific technologies testing have been realized in 2007: a "Heat Transfer Test Facility", a "Helium Test Facility", a "Pebble Bed Micro Model" and an "Electro-magnetic blower". A fuel laboratory developed manufacturing processes of TRISO fuel particles and quality assurance testing techniques in collaboration with NECSA and successfully manufactured coated fuel particles with enriched uranium in December 2008.

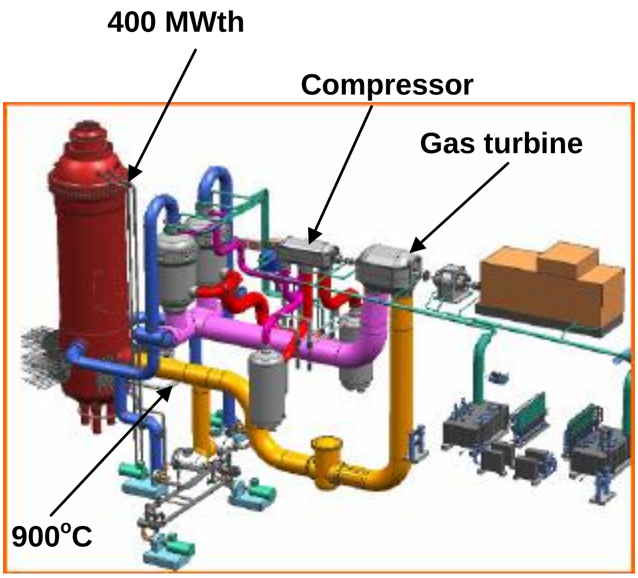

Figure 2: Lay-out of initial 165 MW_e PBMR project

In 2009 the PBMR project, like other projects of nuclear equipment in South Africa, faced funding difficulties and happened to have its business plan re-oriented towards the supply of industrial process heat. The current focus of the PBMR is on onsite power, cogeneration, desalination and direct process heat delivery. Target process heat applications include coal to liquid or gaseous fuels, petrochemicals, ammonia/fertilizer, refineries, oil sand recovery, bulk hydrogen for future transportation and water desalination. Thus, PBMR Ltd started developing options for commercial fleets with Sasol for producing synthetic fuels from coal, with Eskom for electricity, as well as with US and Canadian cogeneration end users including oil sand producers. The PBMR project was accordingly revisited to develop one standard design that meets all requirements for these varied applications, thus leading to a cogeneration steam plant with a thermal power of 200 MW_{th}, a helium temperature of 750°C at core outlet and a steam generator directly placed in the primary loop. A conventional sub-critical steam turbine is selected for first generation plants whereas super-critical cycles can be considered for next generation plants.

IV-C – Next Generation Nuclear Project (NGNP) in the United States

US-DOE initiated exploration of the NGNP[3] concept as part of the Generation IV Nuclear Systems Initiative in 2003. The NGNP project was then mandated by the US Energy Policy Act of August 8, 2005 as a high-temperature gas-cooled reactor intended for high-efficiency electricity production, high-temperature process heat generation, and nuclear-assisted hydrogen production at the Idaho National Laboratory (INL). It would be co-located with an industrial plant that would use process heat from the reactor and could operate in 2021. Pre-conceptual and conceptual design studies have been conducted under contracts awarded in 2006 and 2008 by US-DOE to AREVA, General Atomics and Westinghouse. General Atomics and AREVA are putting forward their GT-MHR and Antares concepts of prismatic block-type high temperature reactor whereas Westinghouse is supporting the Pebble Bed Modular Reactor. The current NGNP concept employs an indirect power conversion that uses intermediate heat exchangers to transfer heat from the reactor primary loop. The secondary loop may be used as a heat source for the production of electricity, hydrogen, or other industrial uses. A number of studies as a part of the conceptual design have identified bounding conditions as follows: i) At this time there are no discriminating technical factors that favor pebble bed or prismatic design over another, ii) One-size-fits-all approach is not necessarily consistent with all off the end user needs, and iii) User needs indicate that the initial gas outlet temperature will be in the 750-800°C range. However, R&D will continue to enable full potential as well (950°C).

Fuel development irradiation is being conducted at the INL Advanced Test Reactor on high temperature fuel kernels made at BWXT and coated at Oak Ridge National Laboratory. Additional research is also proceeding to better understand irradiated graphite stability under load at operating temperatures, qualify high-temperature metallic alloys, and to support development of physics, thermo-fluids, and accident simulation codes. The NGNP project took another step in August 2008 when the US-DOE and the NRC submitted a joint licensing plan leading to a licence application filed in 2013. DOE is currently developing a final strategy for partnering with the industry (nuclear vendors and potential users of process heat in sectors such as oil-, chemistry or steelmaking) to drive the development of the NGNP project.

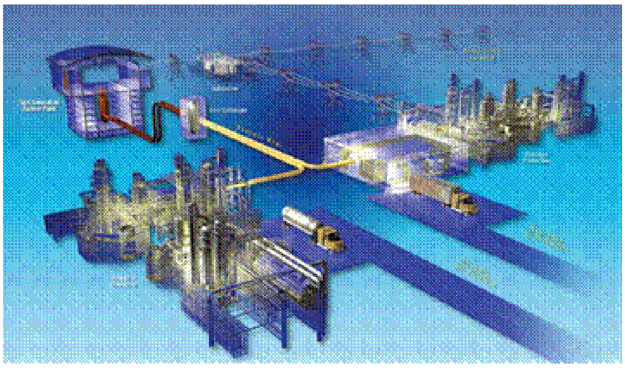

Figure 3: Artist view of NGNP supporting both applications of nuclear production of hydrogen and synthetic hydrocarbon fuel from coal

IV-D – Gas Turbine High Temperature Reactor (GTHTR-300C) in Japan

The Japan Atomic Energy Agency (JAEA) is currently conducting research and development for the project of "*Gas Turbine High Temperature Reactor 300–Cogeneration*" (*GTHTR300C*)[4] (Figure 4) that is dedicated to CO_2 emission free cogeneration of electricity and hydrogen by sulfur-iodine thermo-chemical water splitting process.

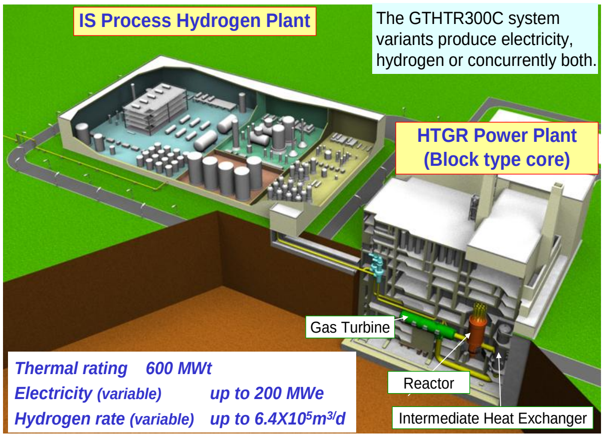

Figure 4: Gas Turbine High Temperature Reactor 300 for Cogeneration (GTHTR300C)

With a thermal power of 600 MW and a block-type core with an exit temperature of 950°C, the GTHTR300C is believed to be highly efficient and economically competitive for cogenerated hydrogen and electricity. The Intermediate Heat Exchanger (IHX) and the gas turbine are installed in series in the primary circuit so that heat over 900°C (170 MW_{th}) can be efficiently used for hydrogen production and helium at 850°C can be used for generating electricity. The GTHTR300C thus allows a co-generation of about 200 MW_e and 640 000 m^3/day of hydrogen by the thermo-chemical sulfur-iodine process (enough to serve about 170 000 fuel cell vehicles).

In order to minimize cost and risk of deployment, the GTHTR300C is based on HTTR-derivative technologies, on current helium turbine power conversion and on technologies under development for the thermo-chemical water splitting process. A technology roadmap of nuclear hydrogen production was issued by the Atomic Energy Commission of Japan in July 2008. It envisions the introduction of commercial HTGR hydrogen production around 2030 and foresees by 2020 a prototype of commercial reactor based on technology and reliability demonstrations achievable in the HTTR and the associated system dedicated to pre-industrial sulfur-iodine cycle demonstrations.

IV-E – Nuclear Hydrogen Development and Demonstration (NHDD) in Korea

In a context of wilful development of hydrogen technologies to prepare the hydrogen economy in the Republic of Korea, the Korean Atomic Energy Commission approved a national nuclear hydrogen program in Dec. '08 that consists of two major projects:

- A project of key technologies development for nuclear hydrogen, and
- A project of Nuclear Hydrogen Development and Demonstration (NHDD).[5]

The project of key technologies development was launched at KAERI in 2006. It focuses on the development and validation of technologies that are key to nuclear hydrogen systems. Topics involved include design and computational tools, high-temperature materials and components, TRISO fuel particle manufacturing and performance testing, and the sulfur-iodine thermo-chemical hydrogen production process. The project will extend up to 2017 in phase with goals of GIF's and NHDD's projects. The NHDD project aims at designing, constructing a nuclear hydrogen production system and demonstrating its safe and reliable operation. The project is expected to be launched in 2010 with target dates of 2022 for the completion of construction and 2026 for prototypical demonstrations. Reference options for such a nuclear hydrogen production system consist of a very high temperature reactor of 200 MW_{th} with a core outlet temperature of 950°C, 5 modules of hydrogen production based on the sulfur-iodine water-splitting process, and an intermediate heat transport loop between the reactor and the hydrogen plant. A cooled reactor vessel design is adopted to make use of domestic manufacturing capabilities. Both the prismatic block and the pebble bed cores are considered at this stage. Commercial prospects are at an early stage of discussion.

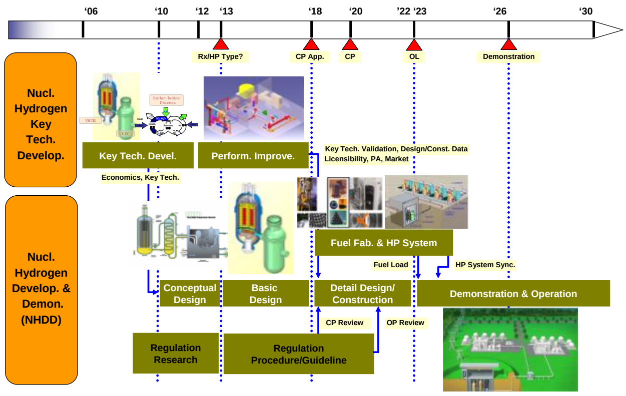

Figure 5: National Nuclear Hydrogen Project Plan (approved by the AEC of Republic of Korea in Dec. '08)

IV-F – Multinational cooperation on the VHTR System in the Generation IV International Forum[6]

The potential of a VHTR at 900-1 000°C to match temperature requirements for advanced hydrogen production processes based on electro- or thermo-chemical water splitting processes was the initial driver for this reactor type to be selected in 2002 among the six Generation IV Systems. Missions of the VHTR have expanded since then to cogeneration of electricity and process heat for varied industrial applications. This system experiences a sustained interest from all active members of the GIF since its beginning. The VHTR System Arrangement was signed in December 2006 by Canada, EURATOM, France, Japan, the Republic of Korea, Switzerland and the United-States. The People's Republic of China signed this Arrangement in October 2008 and the Republic of South Africa is expected to sign it in 2009. Multinational cooperation in the GIF complements national R&D efforts for current projects of reactor at 700-850°C and also develops technology breakthroughs for the VHTR aiming at 900-1 000°C. Projects on "Fuel and fuel cycle" and "Hydrogen production" became effective in January and March 2008 and a project on "Materials" will become effective in the fall of 2009. A project on "Computational methods, validation and bench–marking" will be ready for signature at the end of 2009. Cooperative work on TRISO fuel includes sharing irradiation experiments, post irradiation evaluation facilities and constituent materials properties. Cooperation on hydrogen production processes allowed to share the realization and results of laboratory scale experiments on the sulfur-iodine and high temperature electrolysis, to advance the development of catalysts and share results of technical and economic assessments of varied candidate water splitting processes. Cooperative development of materials covers graphite, advanced super-alloys (nickel-based and

9Cr ferritic steels) and composite ceramics. Results are compiled in a common data base operated by the Oak Ridge National Laboratory. Specific Agreements will be worked out to frame exchanges between cooperative R&D in the GIF and VHTR related projects so as to assure a fair treatment of R&D results generated by GIF members and their privileged access to operating parameters of prototype reactors in fair conditions.

IV-G – HTR Technology Network and ooperative R&D in Europe: towards a Demonstrator?

A partnership of European nuclear industrial and research organisations has been established with the creation in 2000 of the (European) “HTR Technology Network” (HTR-TN) for developing HTR technology. HTR-TN has played since then a prominent role in defining a strategy for European R&D on HTRs and implementing this strategy in Euratom Framework Programmes (FP) since 2000 (5^{th} FP). This led to revive in the 6^{th} FP (2002-06) the past experience in Europe on HTR design tools and technologies (fuel, materials, helium systems’ technology, coupling technologies…) in a program called RAPHAEL.[7] This set the stage for EURATOM to bring consistent contributions to VHTR R&D Projects in the Generation IV International Forum and for approaching industrial sectors potentially interested in low-carbon process heat. Investigating prospects of nuclear process heat applications for oil, chemical or steelmaking industries is currently in progress within the project Europairs that was launched in 2009 (FP7) and where potential end-users specify their needs and interact with the designers and safety authorities.

In order to achieve the industrial coupling between a nuclear heat source and industrial processes, the unfortunate scission between nuclear and non-nuclear communities and cooperative programs in Europe should be overcome. Besides, as the licensing of modular HTR/VHTRs and their coupling with chemical plants are critical issues, early interactions should be organised with regulators and Technical Safety Organizations. HTR/VHTR projects will continue in FP7, as initiated by RAPHAEL in FP6, and will contribute to VHTR R&D Projects of the Generation IV International Forum.

The launching in September 2007 of a Technology Platform on “Sustainable Nuclear Energy” (SNE-TP)[8] initiated a process of building an integrated and consistent program of R&D among European stakeholders along three directions: light water reactors, fast-neutron reactors with a closed fuel cycle and high temperature nuclear technologies for the cogeneration of non-electricity products.

Marketing prospects of high temperature nuclear heat are currently too uncertain for stakeholders of the nuclear industry and potential users of HTR energy products to envision yet building a prototype of next generation HTR in Europe. This issue will be debated versus the alternative that consists of having a significant European participation in a prototype abroad such as the NGNP in the US, PBMR in South Africa or HTR-PM in China.

V. FUTURE PROSPECTS

The unique capability of VHTRs to produce process heat above 600°C makes them an efficient reactor type to displace fossil fuels in a number of varied applications such as producing electricity, non-conventional hydrocarbon fuels from coal or biomass, and process heat for energy intensive industries (oil refining, petro-chemistry, chemistry, steelmaking…). Current research programs within GIF and specific country programs address major developments, demonstration and deployment issues. In particular, the multinational cooperation within the Generation IV International Forum allows to share efforts to advance VHTR technologies and to speed-up the development of breakthroughs for this reactor type. Furthermore, both experimental reactors in operation in Japan (HTTR) and in China (HTR-10) offer unique opportunities to qualify precursor VHTR technologies and design codes. Finally, ongoing projects of next generation HTR prototypes and projected pre-industrial demonstrations pave the way for the deployment worldwide of extended applications of nuclear power beyond the production of electricity and derived energy products that are accessible to Gen III light water reactors. These unique capabilities that enable increased reductions of CO_2 emissions, together with the versatility of VHTRs attest the high potential of this reactor type and spurs the interest of all GIF active members, as well as a growing participation in associated R&D as the GIF expands.

Acknowledgements

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Nomenclature

AEC – Atomic Energy Commission

AVR – Arbeitsgemeinschaft Versuch Reaktor

FP6, FP7 – 6^{th}, 7^{th} European R&D Framework Programme

GIF – Generation IV International Forum

GT-MHR – Gas Turbine Modular Helium-cooled Reactor

HTR – High Temperature Reactor

HTR-10 – High Temperature Test Reactor (10 MW_{th})

HTR-PM – High Temperature Reactor – Pebble-bed Module

HTR-TN – High Temperature Reactor Technology Network

HTTR – High Temperature Test engineering Reactor

IHX – Intermediate Heat eXchanger

INET – Institute of Nuclear and New Energy Technology

INL – Idaho National Laboratory

KAERI – Korea Atomic Energy Research Institute

MHTGR – Modular High Temperature Gas-cooled Reactor

MW_e – Megawatt (electric)

MW_{th} – Megawatt (thermal)

NECSA – South African Nuclear Energy Corporation

NGNP – Next Generation Nuclear Project

NHDD – Nuclear Hydrogen Development and Demonstration

NRC – Nuclear Regulatory Commission

PBMR – Pebble Bed Modular Reactor

R&D – Research and Development

SNE-TP – European Sustainable Nuclear Energy Technology Platform

THTR – Thorium High Temperature Reactor

TRISO – Tri-Structural Isotropic Fuel

US-DOE – Department Of Energy of the United-States

VHTR – Very High Temperature Reactor

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